DETONATION OF ELONGATED CHARGES WITH CAVITIES

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"Channel" effects have been investigated in elongated charges of cast Composition B with cavities of various shapes. The existence of a transient regime has been established and the velocities of the channel shock waves in the regime have been measured. The parameters of the jets formed in tubular charges are estimated.

It is known that the detonation of elongated explosive charges with cavities is accompanied by distinctive "channel" phenomena.

A group of British investigators has published a series of papers on the detonation of tubular charges with an air cavity [1–3]. They have given the following description of the process.

A powerful shock wave is created in the cavity of the detonating tubular charge. On a length of several tens of cavity diameters the velocity of this wave is almost constant and exceeds the usual detonation velocity for a given explosive by approximately 75% for dense and 65% for low-density materials. Subsequently, the shock wave becomes attenuated as a result of losses associated with interaction with the charge walls. The attenuation may be caused by a reduction in the supply of energy to the wave as a result of the thinning of the walls by erosion or premature partial decomposition of the explosive. During the attenuation of the primary shock a secondary shock, whose velocity also considerably exceeds the detonation velocity, is generated in the region between the primary shock front and the detonation front.

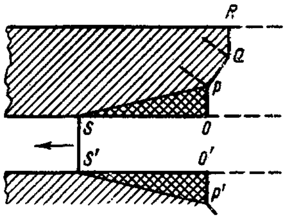

Fig. 1

On a small initial interval the rate of propagation of detonation along the outer surface of the charge is equal to the usual value of the detonation velocity for a given explosive; then it increases abruptly to a value that depends only slightly on the initial density of the explosive (the increase is several percent for dense explosives and several tens of percent for low-density explosives). The assumed structure of the detonation wave is shown in Fig. 1, where QR is the undisturbed part of the initial plane detonation wave and SS' is the front of the air shock in the channel. The shock wave SS' excites a compression wave SP in the explosive. In the region OSP the explosive is compressed and its detonation velocity exceeds the initial value, so that the detonation wave OP, propagating through the compressed explosive, leads the undisturbed wave QR. PQ is a conical detonation front moving at normal velocity through the uncompressed explosive. At a certain instant the point Q reaches the outer surface of the charge, which causes an abrupt increase in the observed detonation velocity.

It has been established that in dense charges detonation is not initiated from the surface of the channel; in low-density charges this effect is observed in individual experiments, with a considerable lag relative to the instant of passage of the shock wave. It is relatively easy to initiate detonation in the solid cap of explosive closing the outlet opening of the channel; Woodhead [2] has called this effect advance detonation.

If the explosive is capable of detonating in two regimes (high-velocity and low-velocity), the differences between the velocities of the channel wave front and the detonation front are almost the same in both regimes.

Special experiments have shown that the longitudinal displacements of the charge preceding arrival of the detonation wave are negligibly small.

It should be noted that the model represented by Fig. 1 is not universal. For different explosives and at different initial densities compaction in the compression wave may lead both to an increase and to a decrease in detonation velocity.

Experiments with tubular charges are also described in [4–9]; the extensive experiments performed by Ahrens deserve special attention [5].

In explosives practice the cross sections of blast holes and boreholes are frequently incompletely filled with explosive. The presence of long cavities between the surface of the charge and the surrounding medium may affect the detonation conditions and may even cause total quenching. This is known as the "channel effect." The channel effect is evidently similar to the phenomena associated with the detonation of tubular charges.

The channel effect has been the subject of extensive research. It has been established that brightly luminous shock waves leading the detonation front are formed in the cavities.

It has been shown in various ways that the channel shock generates a compression shock in the unreacted explosive and therefore may considerably modify the structure of the detonation wave. Semiempirical calculations of the channel wave-compression wave system have been made for the case of a plane layer of easily compacted explosive with a plane gap between the surface of the explosive and a solid wall. Explanations have been proposed for the detonation quenching effect. These relate the instant of quenching with the occupation of the cross section of the undetonated part of the charge by the compression wave and saturation of the explosive with compressed gas from the region of the channel wave. As with tubular charges, a secondary shock is formed in the region between the primary shock front and the detonation front. In this region, moreover, explosive eroded from the surface of the charge is observed to burn. Detailed descriptions of these phenomena may be found, for example, in [10–12].

Below we present certain results of an experimental investigation of the detonation of charges with elongated cavities obtained in the course of developing charges for accelerating solid particles [9].

We investigated charges of several types composed of cast Composition B (50-50); the cross sections are illustrated in Fig. 2, where 1 denotes plastic and 2 glass. The tubular charges were composed of sections 5–10 channel diameters long, the other types of charges were monolithic.

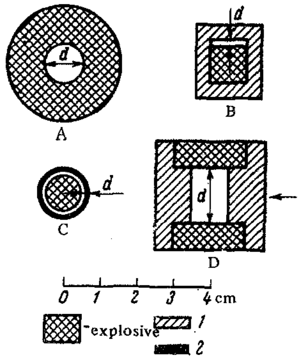

Fig. 2

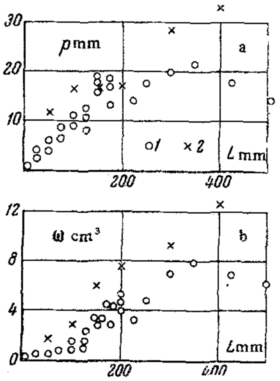

Fig. 3

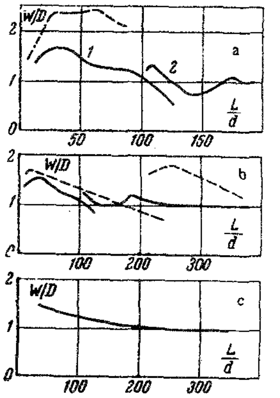

Fig. 4

We measured the parameters of the craters formed by the explosion of tubular charges in massive mild-steel targets. The charges were arranged at right angles to the surface of the target, the distance from the outlet section of the charge to the surface of the target being 13 mm. The dependence of crater depth and crater volume on charge length is shown in Fig. 3a, b. The level of the initial surface of the target was taken as the upper edge of the crater. Points 1 relate to an unlined charge of type A, points 2 were obtained for a similar charge whose cavity was lined with an ebonite tube with outside diameter 11.5 mm, inside diameter 10 mm. It follows from the results of the experiments that the unlined tubular charge produces the largest crater at a relative cavity elongation of approximately 35 channel diameters.

A series of experiments was conducted in order to study the behavior of the channel waves at large cavity elongations. In these experiments the process was continuously recorded with a high-speed photorecorder and, in certain cases, the velocity of the channel wave front in charges of types A, B, and C was measured by means of contact probes. The results, averaged over 2–3 experiments on each type of charge, are presented in Fig. 4a, b, c, where the following notation has been employed: W–shock front velocity, D–detonation velocity (~ 7.6 km/sec), L–distance along charge from beginning of cavity, d–characteristic transverse dimension of cavity (see Fig. 2).

The results of experiments with tubular charges similar to charge A (outside diameter 15 mm, inside diameter 5 mm) are shown in Fig. 4a. The solid curves 1 and 2, respectively, represent the dependence of the velocities of the primary and secondary channel shock fronts on the dimensionless distance L/d along the charge at a cavity air pressure of 1 atm. The results of experiments with charge A at underpressures up to 1 mm Hg are represented by the dashed curve.

In Fig. 4b solid lines 1 and 2 represent the results of experiments with charges B in air; the dashed line represents the data of [11], where charges similar to charge B, but composed of finely dispersed TNT with a density of 0.5 g/cm^3 were employed.

The results of the experiments with charge C are shown in Fig. 4c. From the data of Fig. 4a, b, c it follows that the detonation of charges with an elongated cavity is usually accompanied by a transient process ending in the establishment of steady-state conditions at a certain distance from the beginning of the cavity. In the steady-state regime the channel wave moves with a certain constant lead relative to the detonation front. In our experiments, the propagation velocity of the steady-state regime coincided, within the limits of accuracy of the measurements, with the detonation velocity of an open solid charge. In the transient regime two channel waves were observed in charges A and B, in charge C only one (perhaps in this case there was a secondary wave, but it was not detected owing to the relative insensitivity of the experiment). The fluctuations of the velocity of the secondary wave front are associated with the fact that initially it is propagated through a region of nonuniform flow created by the primary wave. The end points of curves 1 in Fig. 4a, b correspond to the points at which the waves merge.

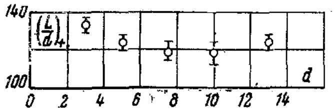

Fig. 5

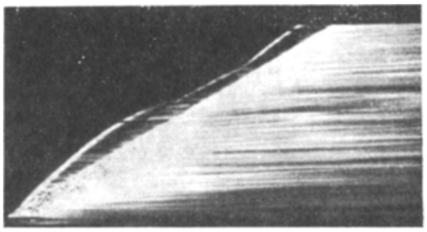

Fig. 6

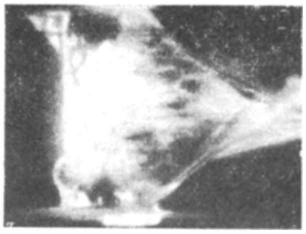

Fig. 7

We also investigated the possibility of simulating channel effects in accordance with the principle of geometric similarity. The following factors may be responsible for deviations from this principle: near-critical effects in small charges, nonsimulability of boundary and erosion processes. We conducted a series of experiments with tubular charges whose outside diameter, as in the case of charge A, was three times greater than the cavity diameter. The results of the measurements are presented in Fig. 5 in the form of the dependence of the dimensionless coordinate $(L/d)_+$ of the point at which the primary and secondary waves merge on the cavity diameter. The data of Fig. 5 indicate the presence of a weak scale effect. Apparently, as the scale of the charge varies, qualitative changes may also appear in the channel effect mechanism. Thus, in connection with the detonation of a charge with cavity diameter 3 mm we noted the appearance of a third channel wave in the region of 160–210 and more channel diameters. The record of the detonation of this charge in L-t coordinates is reproduced in Fig. 6.

It may be assumed that in the transient regime, approximately on the interval corresponding to the ascending branches of curves 1, a jet of explosion products, which sustains the air shock, is formed in the cavity. At the beginning of the transient regime explosion products accumulate in the region between the detonation front and the channel wave front, and then the explosion products flow out of this region through the axial zone until the steady-state regime is established. This assumption makes it possible to explain the increase in the cratering ability of tubular charges up to elongations of several tens of channel diameters (Fig. 3), the possibility of using tubular charges to accelerate solid particles to velocities of 8–14 km/sec [9], and the behavior of curves 1 in Fig. 4a, b.

Several experiments were performed in order to investigate the structure of the zone in which a jet may be formed. For this purpose we photographed the detonation process of charge D with the photorecorder operating in the continuous mode through a transverse slit 0.25 mm wide (the direction of filming is shown by the arrow in Fig. 2). Typical records are reproduced in Figs. 7, 8, and 9. The distance between the slit and the beginning of the cavity was 75 mm (L/d = 5) in Fig. 7, 120 mm in Fig. 8, and 240 mm in Fig. 9. The scanning speed was so selected that the scales of the image in the longitudinal and transverse directions were approximately equal. In Figs. 7, 8, and 9 the jets cannot be detected directly; indirect proof of their existence is supplied by the presence of a gap between the detonation wave and the trailing edge of the brightly luminescent layer of air compressed in the shock wave (the velocity of the piston sustaining the air shock is much higher than the detonation velocity).

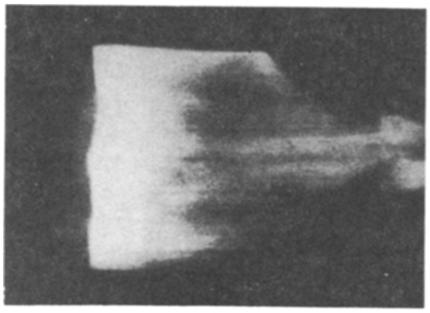

Fig. 8

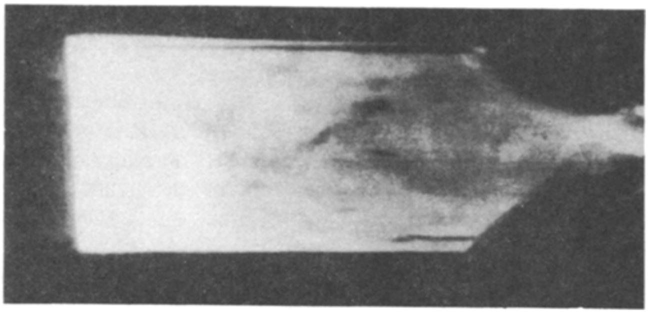

Fig. 9

The jet parameters can be estimated in two ways. The first method gives a lower bound of the jet parameter ρv^2 on the basis of the acceleration of solid particles by tubular charges [9]. A charge of type A 250 mm long accelerates a steel pellet 1 mm in diameter to 7.3 km/sec on a 50-mm path. The force F acting on a sphere in a supersonic flow is given by the formula [13]

$$F \simeq 1.43\, \rho v^2 r^2.$$

Here, ρ is the density of the undisturbed flow, v is its velocity relative to the sphere, and r is the radius of the sphere. By means of this relation, by equating the final kinetic energy of the sphere to the product of F and the acceleration path, we find the mean value of ρv^2 during acceleration; it is equal to $6 \cdot 10^{10}$ dyne/cm^2. In reality, owing to the gradual decrease in flow velocity relative to the sphere and the nonuniform application of the load during acceleration $\rho v^2 > 6 \cdot 10^{10}$ dyne/cm^2. The velocity of the jet evidently lies in the interval 10–15 km/sec, so that its density is not less than 0.025–0.06 g/cm^3.

The second method consists in using the data of Fig. 3b. For a rough estimate it may be assumed that the volume of the crater in the target is proportional to the energy expended on forming it. The slope of the ascending part of the curve in Fig. 3b is ~ 0.265 cm^3 per centimeter of charge length. The formation of a crater with a volume of 0.265 cm^3 in mild steel requires the expenditure of energy on the order of 1.5 kJ [14], whereas the total energy of the explosive per centimeter of charge is about 50 kJ. Thus, the cratering efficiency of a tubular charge is on the order of 3%. Since only part of the energy of the jet is expended on crater formation, the fraction of charge energy imparted to the jet must be still greater.

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